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Innovative Design of Three-Axis Jig for Drilling Enhancement

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ABSTRACT

Jigs and fixtures serve as industrial tools to achieve precise and standardized production of interchangeable parts, ensuring consistency and compatibility in manufacturing operations. This study observes the improvement of the design and function of the jig. The study aims to analyze product costs and determine maximum profits and return on investment. The original Plate Jig had two problems: the absence of a marking function and limitations in holding curved-sided workpieces. This study focuses on enhancing the drilling process by introducing a marking and ruler system and redesigning the locator. These improvements will increase efficiency and ease of use for operators. The raw material must undergo the drilling and heat, cutting, polishing, and CNC Milling process to produce this product. The method of creating a Staircase Locator by undergoing a CNC Milling process that is designed using the SURFCAM Software is discussed in this paper. After the cost analysis, the profits can earn in RM176.02, and the return of investment is 68.98%. By employing 3-axis jigs, the measurement process can be significantly expedited.

Keywords: Jigs and fixtures, Innovative design, CNC Milling process, Three-Axis Jig, Drilling Enhancement.

1. INTRODUCTION

Jigs and fixtures are crucial tools in industrial manufacturing that offer several benefits, including cost reduction, lower skill requirements, enhanced quality, and increased efficiency [1]. By simplifying the process of positioning and securing workpieces, these tools help reduce labor costs, minimize material waste, and prevent errors, contributing to overall cost savings. They also reduce the skill requirements for operators, allowing less experienced workers to achieve high precision and consistency with minimal training [2]. In terms of quality, jigs and fixtures ensure uniformity and accuracy in production by holding workpieces securely and maintaining consistent positioning, which leads to fewer defects and more reliable products. Efficiency is also significantly improved as these tools streamline operations, reducing setup times, minimizing downtime, and boosting production rates [3]. Jigs, in particular, not only hold the workpiece but also guide the tool during operations, such as drilling, to ensure precise results. On the other hand, fixtures primarily focus on securing and positioning the workpiece without guiding the tool. They are often used in tasks like milling or assembly [4]. Overall, jigs and fixtures are vital in improving accuracy, reducing errors, and standardizing processes, making them indispensable in modern manufacturing [5].

Silva et al. [6] developed a new jig-holding system compatible with three-axis CNC machining centers. This significantly enhanced productivity by enabling the machining of unparalleled planes in a single setup. Using an action research methodology, the study generated practical knowledge transferable to similar organizations, with observed cost savings of up to 40% for

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parts with low geometric complexity and even higher for more complex parts. The system offers a return on investment in under two years, making it affordable for many enterprises. The key settings and recommendations for adopting this system were established, doubling production capacity with a double-sided jig table. Patil and Kherde [7] focused on the importance of work-holding devices like jigs and fixtures in improving product quality, reducing manufacturing time and cost, and ensuring product interchangeability. They highlighted the limitations of traditional fixtures in adapting to rapid design changes, emphasizing the need for modular, flexible fixture systems in small-batch production. They designed explicitly and fabricated a cost-effective jig and fixture for indexing and positioning cylindrical components in drilling machines, addressing the challenges of circular component handling. The effectiveness of the jigs and fixtures used significantly influences the performance quality of such operations. Prajapati et al. [8] reported that many industries today use CNC machines to produce turbo machinery components like turbine blades, impellers, and rotors, where minimizing workpiece deformation is crucial for maintaining machining accuracy. Fixtures, which hold and support workpieces during manufacturing, help align the cutting tool but do not guide it. L&T–MHPS Turbine Generators Pvt Ltd designs and manufactures turbine blade parts, many of which require sophisticated fixturing for machining. Recently, the company has shifted from using a 4-axis CNC fixture system to designing a 5-axis fixture system, eliminating the need for different fixtures for each machine and improving efficiency.

Pachbhai and Raut [9] reviewed various clamping methodologies used in machining fixtures to minimize workpiece deformation and maintain machining accuracy. It highlights the importance of selecting optimal fixturing elements like locators and clamps based on application needs across different industries. Currently, fixture setups are done manually, requiring more cycle time for loading and unloading, which impacts productivity. To address this, they emphasized the need for improved systems to enhance productivity, reduce operation time, and ensure high-quality machining operations. Liu [10] reported that the shift from dedicated fixtures to modular fixturing systems is gaining popularity in manufacturing due to increased flexibility, though selecting and assembling suitable modules can be challenging. Liu's research offered a systematic design method to assist users in transitioning from dedicated to modular fixtures by classifying modules into five functional groups and selecting them based on specific fixture requirements. This approach enables users to create an efficient and cost-effective modular fixturing system. Awang et al. [11] highlighted that in the Jigs and Fixtures Design course, students were tasked with developing specific jig designs, covering processes from idea generation to prototype development. However, previous students faced challenges due to limited equipment and prototype skills, affecting the quality of their work. A modular system using CAD software was developed to address this, allowing students to select pre-made components for jig development, reducing design time and helping them better visualize their final product.

The increasing demand for complete machining and assembly in jigs, without pre-machining individual components, is driving the development of advanced machining technologies, such as flexible and mobile equipment [12]. Future aircraft designs involving significant subcomponents with vast tolerances require adaptive machines capable of drilling deep, wide holes in titanium and other materials without causing deformation. These machines must also handle circular interpolation in stack materials like titanium, aluminum, and carbon fiber while maintaining high tolerances and preventing delamination. Neumann [12] highlighted the need for high productivity and flexible machining around large assemblies, such as wing boxes, which necessitates compact, agile machines operating in tight spaces from multiple angles. Mohammed and Tariq [13] explored the performance of drill jigs by modeling and assembly using PRO E software and analyzing them with Ansys to enhance design efficiency, reduce costs, and improve production through interchangeable parts. To stay competitive in a growing market, industrialists must focus on increasing production and improving quality while reducing costs. This leads to adopting automation and tooling aids like jigs and fixtures, which offer lower initial investments and higher productivity. Rempel et al. [14] focused on designing a drill jig to enhance efficiency in drilling operations within small and medium-scale manufacturing industries. They aimed to reduce production costs, improve product quality, increase production rates, and minimize operation time, particularly for a cylinder actuator's head and cover parts. Using SolidEdge V19 for modeling and ANSYS Workbench for stress analysis, the jig's design is finalized, manufactured, and tested for performance.

The plate Jigs [15] chosen for this project emphasized accuracy and included built-in clamps. In accordance with the needs of the workpiece, they can be customized with or without bushings and legs. Drill bushes are used in plate jigs to guide drills and hold the workpiece in place, ensuring excellent precision and repeatability. In today's rapidly evolving industrial landscape, efficiency and accuracy are critical factors for success in various sectors, including manufacturing, construction, and fabrication. However, traditional drilling machine tables have often posed challenges regarding performance, versatility, and ease of use [16]. The time taken on the measuring process will decrease using these 3-axis jigs. To address these issues and cater to the current demands of the industry, a new era of drilling machine table innovation has emerged. These innovative solutions are designed to revolutionize drilling by incorporating advanced technologies and ergonomic designs. The measuring equipment was applied to the drilling table, and two scaling shafts were moved in 3-axis mode. The design was upgraded from a non-practical measuring style to a cylinder-type scaling range. This simplified design is still functional while saving raw materials and reducing space around the cutting area. The materials for this project include SKD 11, stainless steel 304, S45C, and Alloy Steel. For SKD 11, the material used to make a 3-axis base, 200mm cylinder, and busher holder will be cut using a grinding machine. The L-locator in this design can be replaced with another locator, like the Vee-locator. The operators can rapidly change the locator when the workpiece has a curved side by adding the removable locator, which also helps to boost productivity. Reduce the marking ruler's material to lower the product's price while maintaining the marking ruler's function. The project has the potential to save costs while increasing production. Costs may decrease due to simple assembly, waste reduction, and lower labor costs. Therefore, this project aims to improve the design and function of the jig. This project also analyzed the product cost and calculated the maximum profits and return of investment. Enhancing the jig's design and function increases the individual's efficiency and productivity and reduces operation time.

2. MATERIAL AND METHODS

SolidWorks software created and designed each part of the product in this project. SURFCAM Software was used to simulate the parts required for manufacture using a CNC milling machine. In today's rapidly evolving industrial landscape, efficiency and precision are critical factors for success in various sectors, including manufacturing, construction, and fabrication. However, traditional drilling machine tables have often posed challenges regarding performance, versatility, and ease of use. The time taken on the measuring process will decrease using these 3-axis jigs. To address these issues and cater to the current demands of the industry, a new era of drilling machine table innovation has emerged. These innovative solutions are designed to revolutionize drilling by incorporating advanced technologies and ergonomic designs. The aim is to enhance productivity, improve accuracy, and streamline operations while addressing safety concerns and offering greater flexibility. The existing drilling table only clamps the workpiece. The workpiece needs to be manually measured on another table. After that, it needs to clamp on the drilling table. The process will be delayed due to changing table procedures. However, the problem will be solved after combining the processes at one site. The measuring equipment was applied to the drilling table with two scaling shafts moved in a 3-axis mode.

2.1 Product Design

The marking ruler is the first design of the part we designed for improvement. The function of the marking ruler is to mark the workpiece after the workpiece is placed on the jig instead of using a ruler to mark the workpiece before it is placed on the jig. Next, it can reduce the time for marking the workpieces individually because the marking ruler is fixed after we mark the first workpiece. All we need to do is remove and add a new workpiece. Figure 1 shows the idea of a 3-axis jig. Figure 2 depicts the orthographic views of the assembled model. Figure 3 shows the exploded view of the entire 3-axis jig.

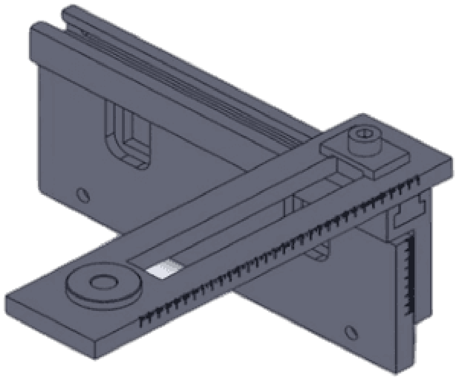


Figure 1: First design of 3-axis jig idea.

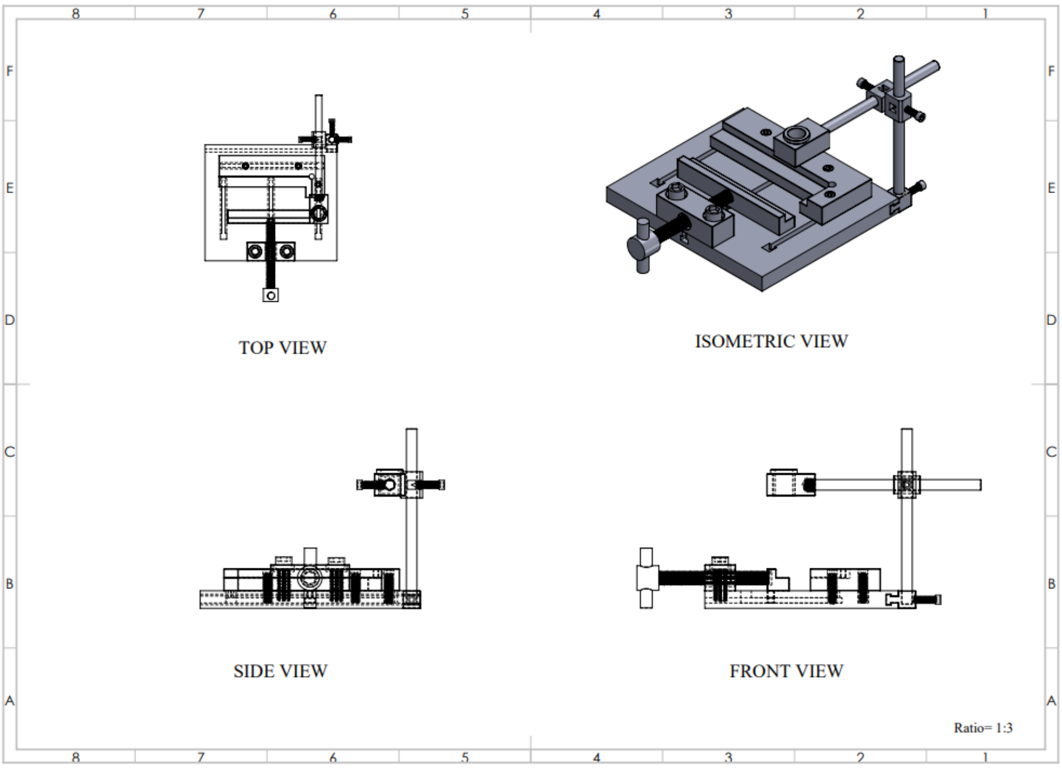


Figure 2: Orthographic view engineering drawing of 3-axis Jig.

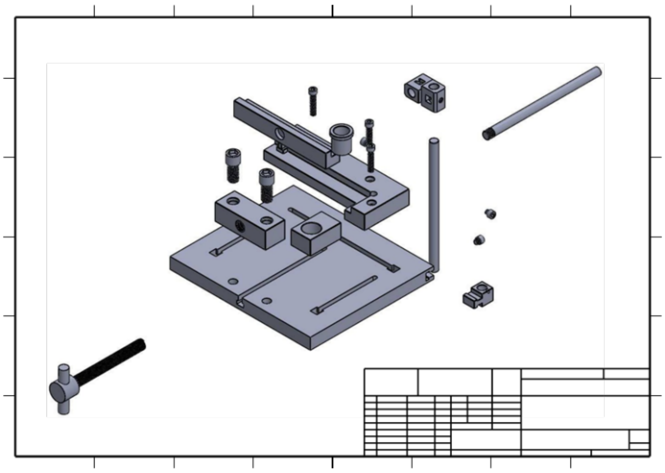


Figure 3: Exploded view of the 3-axis jig.

2.2 Manufacturing Process

Figure 4 presents a flowchart outlining the production process for the components and parts of a 3-axis jig. The diagram clearly illustrates the sequential steps involved, from selecting raw materials, such as SKD 11, Stainless Steel 304, S45C, and Alloy Steel. It then details each phase, including cutting, threading, polishing, and painting, along with various machines such as the grinding machine, hand angle grinder, and CNC milling machine. The flowchart organizes the entire manufacturing process, emphasizing the efficiency and precision required at each step to ensure the production of high-quality jig components. This flowchart structure highlights key production activities and tools, making the process understandable.

The production process utilizes SKD 11, Stainless Steel 304, S45C, and Alloy Steel. The material is initially cut using a grinding machine for components like the 3-axis base, a 200 mm cylinder, and a busher holder made from SKD 11. Manufacturing the 3-axis jig base involves using a hand-angle grinder and a thread drill machine. First, the SKD 11 plate is cut into pieces based on specified dimensions. A thread drilling process follows, creating threads with 6 mm, 12 mm, and 14 mm diameters. Afterward, the surface of the SKD 11 is polished to ensure precise fitting and accuracy according to specifications. The body of the base, which is not in contact with other parts, is then painted dark green, and accurate measurement scales are marked. The base components are then assembled and tightened using an Allen key screw.

To produce the shaft, an SKD 11 beam is cut into two 200 mm sections using a grinding machine, and the sides are polished with a sandpaper grinder to achieve a smooth surface finish. SURFCAM software is used to create the drawings for the connector and adjustable cylinder holder, and the NC code for these parts is generated. The NC code is then imported into the CNC milling machine, which cuts the alloy steel and S45C parts according to the specified design.

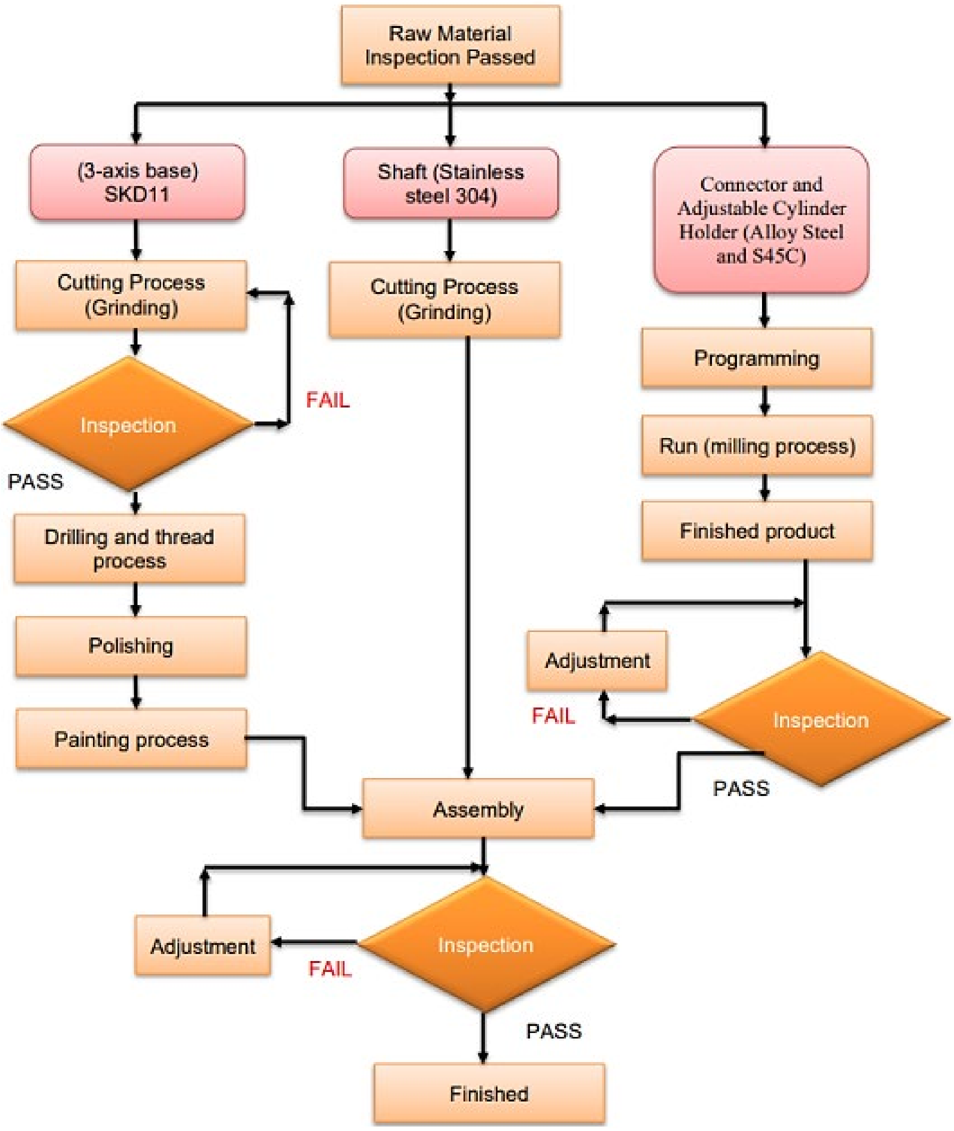


Figure 4: Flowchart of the 3-axis jig components and parts production process.

2.3 Drilling force equation

The product must select the correct and suitable material to absorb the maximum drilling force during the ongoing drilling process.

$$\text{Drilling force} = 1.16 \times k \times d \times (100 \times s)^{0.85} \quad (1)$$

where,
k = material factor
d = the diameter of the drill (mm)
s = feed rate (mm/rev)

3. RESULTS AND DISCUSSION

SURFCAME software was used to design the staircase locator to undergo the CAM process in the CNC Milling Machine. SURFCAME software generated the NC Code to import into the CNC Milling Machine. The alloy steel makes the staircase locator, as shown in Figure 5.

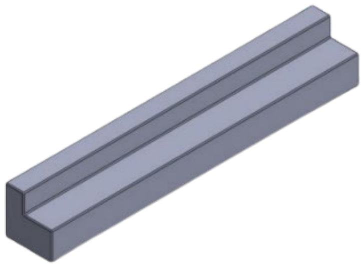


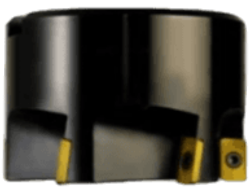
Figure 5: Staircase Locator

3.1 Computer-Aided Manufacturing

First, the material and part are drawn using a rectangular line to set the area and origin location. Next, create the cylinder stock with the value X is 164 mm, Y is 25 mm, and Z is 26 mm with the top view coordinate system style. The next step is to proceed to the face mill process. The top area has been cut to get the smooth surface finish; the amount to remove is 1mm downward. Then, the pocket mill process was located in the middle area of the z-axis. Perform with 6mm– 4 flute – HSS Endmill tool. Moreover, if the cutting is perfect, the toolpath will accept it. Next, the first corner round mill is at the top of the area. Using the 0.5 rad, the surface perfectly follows the drawing specification. Lastly, the second corner mill continued with the pocket-cutting area. After finishing all processes, then proceed to the simulation running.

3.1.1 Tool Selection

The tool types and configurations available for CNC Milling Machines are end mill, face mill, corner rounding tools, slot tools, spot-center drill, twist drill, tap, reamer, and counterbore. The proper tool selection is critical for the milling process because different tools provide different types of milling processes, such as face milling (facing), end milling, pocket milling, and profile milling. The tools used in this project are a 16 mm diameter-3flt-carbide insert mill, 6 mm-4flute-HSS Endmill, and 0.5 mm rad- 3 mm Tip- Corner Round, as shown in Figure 6.



16mm dia – 3 flt – Carbide Insert Mill

6mm – 4 flute – HSS Endmill

0.5mm rad – 3mm Tip – Corner Round

Figure 6: Tool selection in CAM.

3.1.2 Selection of cutting parameter based on material used and cutting simulation

The selection of cutting parameters in this project was carefully made based on the material properties and the cutting simulation processes to ensure efficiency and precision. Four distinct cutting simulation processes were utilized, including the 2-axis face milling process, the 2-axis pocket milling process (as shown in Figure 7), and the 2-axis corner round milling, performed twice for accuracy. These simulations allowed for fine-tuning of critical parameters such as cutting speed, feed rate, and depth of cut to match the specific characteristics of materials like SKD 11, Stainless Steel 304, S45C, and Alloy Steel. Table 1 provides an overview of these machining parameters, highlighting the appropriate settings for each process based on material hardness, tensile strength, and thermal properties. By simulating these cutting operations, the project minimized tool wear, improved surface finish, and reduced machining time, ultimately enhancing the production process's quality and efficiency.

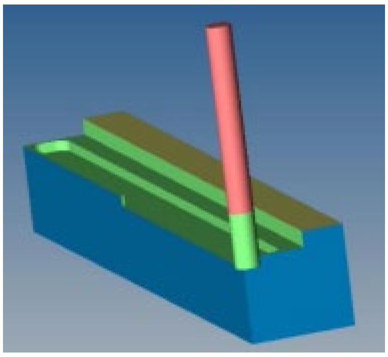


Figure 7: 2-axis pocket process.

Table 1: The parameter of the machining process.

Parameters	Machining Operation		
	2-axis Face Mill	2-axis Pocket Mill	2-Axis Corner Round Mill
Spindle speed (RPM)	1691	4509	5000
Feed rate (MMPM)	532.672	3246.761	1270
Plunge rate	266.336	1623.380	1893.944
Amount to remove (mm)	1	11	24 (from bottom)

3.2 Cost Analysis

The cost analysis calculates the total cost to produce one 3-axis Jig product, and profit and return of investment (ROI) are calculated and determined. The direct and indirect costs, such as machine cost, raw material cost, labor cost, overhead, and head, were considered in the cost analysis.

3.2.1 Direct costs

The cost is calculated to produce 1 product since we want to estimate the total cost (Tables 2 and 3). Direct cost including machine cost (RM48.67) such as hand angle grinder, CNC Milling Machine, and Drilling Machine; raw material cost (RM241.60) such as Allen key screw, SKD11 material, Alloy Steel Material; and labor cost (RM72). Some machines are paid for renting since it is not logical to spend considerable amounts to purchase the machine before the product starts to earn profits. The labor cost is spent on paying the worker 6 hours of work, which involves working for cutting, programming, drilling, polishing, and painting.

Table 2: Price of the type of machine.

Type of machine	Method	Price (RM)
Hand Angle Grinder	Purchase Directly	80.00
CNC Milling Machine	Rent Monthly	1000/month
Drilling Machine	Rent Monthly	80/month
Sand Paper Grinder Machine	Purchase Directly	300.00
	TOTAL	1460.00 = RM48.67/daily

Table 3: Material Cost.

Parts	Quantity	Raw Material	Price (RM)
M12 Allen key Screw	2	304 Stainless Steel	0.40 x2 = 0.80
M6 Allen Key Screw	6	304 Stainless Steel	1.50 x6= 9.00
Bolt	3	Steel Grade 2	0.60 x3= 1.80
Base	1	SKD11	50.00
200mm Cylinder	2		
Busher Holder	1		
Drilling Busher	1	304 Stainless Steel	40.00
Connector	1	Alloy Steel	55.00
Staircase Locator	1		
L-shape Locator	1		
Screw Block	1	S45C	45.00
Adjustable Cylinder Holder	1		
T-shape Screw	1	Steel Grade 2	40.00
		TOTAL	241.60

3.2.2 Indirect costs

Indirect costs are not instantly related to the commercial or industrial activities or are not directly involved in the manufacturing line. The indirect costs include material costs (RM15.20), such as the durable metal paint color; overhead (RM20.30), such as water and electricity bill; labor costs (RM124), such as supervisor and assistant; and taxes 10% regarding the Malaysian Government Regulations.

3.2.3 Selling prices and profits

After accounting for direct and indirect costs, the total production cost for a single 3-axis jig amounts to approximately RM573.98, including taxes. The recommended selling price is RM750, resulting in a profit margin of RM176.02 per unit. This pricing strategy ensures cost recovery and yields a reasonable profit, making the production economically viable. Tables 4 and 5 summarize the fixed and variable costs for the proposed 3-axis jig.

Table 4: Fixed and variable costs.

Type of costing	Costing	Price (RM)
Fixed Cost	Direct materials cost	48.70
	Direct machine cost	241.60
	TOTAL	290.30
Variable Cost	Overhead Cost	20.30
	Indirect material cost	15.20
	Direct labour cost	72.00
	Indirect labour cost	124.00
	TOTAL	231.50

Table 5: Total of fixed and variable costs.

Item	Cost (RM)
Fixed Cost	290.30
Variable Cost	231.50
Total (with 10% taxes)	521.80+(52.18) = 573.98

3.2.4 Return of Investment (ROI)

Business investments are the resources that are put into improving the company, such as time and money. The profit we make from the investments is referred to as the return. ROI [17] is commonly defined as the net profit ratio to total investment cost.

$$\text{ROI} = (\text{Net Profit}/\text{Cost of Investment}) \times 100\% \qquad (2)$$

In this project, the estimated investment cost is RM10,000.00, and the target is to sell 8 product units in a month. If eight units are successfully sold, the profit in one month is RM1408.16 and RM16897.92 in one year. The return of investment in this project is 68.98%.

3.3 Impact and Future

Improving the 3-axis jig could significantly benefit society and the environment by enhancing workpiece positioning, accuracy, and productivity while minimizing waste and production costs. These improvements lead to higher product quality, greater customer satisfaction, and increased job opportunities. However, concerns remain regarding the precision of operations, worker safety, and potential adverse effects on product quality and the environment. For future developments, integrating advanced automation technologies such as robotics and machine learning can further enhance the jig's capabilities through automatic configuration and real-time monitoring. Besides, the Analytical Hierarchy Process (AHP) [18,19] can be integrated into future design works for selecting tangible and intangible factors and applying response surface methodology [20] for factor optimization. Additionally, incorporating digital systems like CAD, CAM, and IoT will enable seamless data exchange and optimization, paving the way for more intelligent manufacturing processes.

4. CONCLUSION

In conclusion, this study successfully achieved its objective of enhancing the design and functionality of the 3-axis jig. The improved jig offers greater versatility, precision, and efficiency across various manufacturing processes by providing a standardized reference point for workpiece positioning, ensuring consistent and high-quality output. By incorporating advanced features and addressing critical issues identified in the initial design, the project also improved safety and ergonomics, creating a more secure and comfortable working environment that reduces the risk of accidents. The upgraded jig design is highly adaptable to evolving production needs, accommodating a range of workpiece sizes and shapes. This flexibility helps minimize errors, rework, and material waste, ultimately boosting production rates while lowering costs. The advancements made in this project lay the groundwork for future research and development in jig design, pushing the boundaries of accuracy and efficiency in industrial processes. Overall, the study makes a significant contribution to the industry by enhancing jig performance, paving the way for continued innovation and higher standards of excellence, productivity, and safety in manufacturing operations.

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